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RESULTS OF A TEN-YEAR FIELD STUDY

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The U. S. Army Construction Engineering Research Laboratories (CERL) has recently completed a 10-year field exposure study of the performance of poly(vinyl chloride) (PVC) roofing membrane materials. The intent of the CERL study was to compare the results of laboratory tests of membrane properties with field performance. Periodically, over the 10 years, CERL visually inspected the roofs to evaluate their performance and removed samples for laboratory characterization of selected mechanical and physical properties. The National Institute of Standards and Technology (NIST) conducted statistical analysis of the 10-year data set. The paper summarizes the results of the field observations and analyses. Membranes from three manufacturers were installed at Chanute Air Force Base, Illinois, Dugway Proving Ground, Utah, and Fort Polk, Louisiana. A major difference in the roof constructions was that, at Chanute, the membranes were ballasted, whereas at Dugway and Fort Polk, they were mechanically attached and adhered.

Performance was generally satisfactory at Dugway and Fort Polk, whereas problems related to shattering and splitting occurred at Chanute. Because of the less-than-satisfactory performance at Chanute, the data analysis focused on determining whether changes in any of the measured properties were consistently different for samples from Chanute than for samples from Dugway and Fort Polk. The results did not, in general, discriminate between the performance of the PVC membranes at Chanute and those at Dugway and Fort Polk. It was observed that, with one exception, the thickness of the samples decreased over time, and the ballasted samples experienced the greatest decrease. This result is discussed in relation to recent data published by the CIB/RILEM Committee on Membrane Roofing Systems.

KEYWORDS

Analysis, building technology, deterioration, field exposure, low-slope roofing, PVC roofing, roofing, single-ply membranes, stability.

INTRODUCTION

The use of synthetic single-ply and polymer-modified bituminous membranes as alternatives to built-up roofing (BUR)

has increased dramatically since the late 1970s.¹ Recognizing the importance of having performance information on these membrane roofing systems, the U.S. Army Corps of Engineers (HQUSACE) asked the Construction Engineering Research Laboratories (USACERL) to investigate such systems for Army facilities.² One of the roofing membrane materials selected for long-term field testing was PVC.³ In 1982 and 1983, test roofs were installed on buildings in three different areas of the country: Chanute Air Force Base, Illinois, Dugway Proving Ground, Utah, and Fort Polk, Louisiana (designated Sites 1, 2 and 3, respectively). Products from three manufacturers (designated Samples 1, 2 and 3) were selected for the study, which was designed to track the performance of the installed roofing over 10 years.⁴ Laboratory testing of mechanical and physical properties was scheduled for membrane samples taken every six months for the first two years and annually thereafter. The exact times of removal of the sample sets varied from the scheduled times because of unforeseen contracting constraints.

Two interim papers have been published on the progress of the study. In 1987, Rosenfield and Wilcoski⁵ reported early test results along with a description of the study design. In 1990, Foltz and Bailey⁶ published results through six years of field exposure. Since then, data for 4 more years of exposure have been gathered and the entire PVC data set statistically analyzed.

This paper summarizes the long-term results of the field test program to evaluate PVC roofing membranes. The results of the statistical analysis of the data set are compared to the reported field performance of the roofing systems. For a complete description of the study, the reader is referred to USACERL Technical Report 96/23 *Long-Term Field Test Results for Polyvinyl Chloride (PVC) Roofing*.⁶

To achieve the objectives of the study, roof systems were selected in 1981 based on earlier USACERL studies. A test plan was developed using standard test methods published by the American Society for Testing and Materials (ASTM). Test sites were then selected and test guide specifications were developed. The construction of the test roofing systems was monitored. Test data were collected for 10 years after construction and the roofs were inspected visually once a year.

DESCRIPTION OF TEST PROGRAM

Description of test roofs

Table 1 gives a summary description of the roof systems. A discussion of the construction of the test roofs can be found in USACERL Technical Report M-343 *Construction of Experimental Polyvinyl Chloride (PVC) Roofing*.⁷ It is important to note that at Chanute, the PVC membranes were installed loose-laid and ballasted. At Dugway Proving Ground and Fort Polk, Samples 1 and 2 were mechanically fastened and Sample 3 was fully adhered.

ASTM categorization of PVC membranes at the time of the study

In 1985, shortly after the initiation of the study, ASTM issued standard specification D 4434⁸, which categorized PVC membranes into Types I, II and III, with Type II subdivided into two grades:

Type I: Unreinforced sheet

Type II: Grade 1 - Unreinforced sheet containing fibers
Grade 2 - Unreinforced sheet containing fabrics

Type III: Reinforced sheet containing fibers or fabric.

The Type II terminology may be misleading as fibers and fabrics are used to reinforce polymeric sheets. By way of explanation, the ASTM Standard D 4434⁸ contained a note that reads:

(F)abrics or fibers may be incorporated into a production process, for example, as a carrier, without appreciably affecting such physical property characteristics of the finished product as tensile strength or ultimate elongation, but may provide other desirable characteristics, such as dimensional stability.

Membranes used in this field study included all three types

as categorized according to D 4434 (Table 1). Sample 1 was a Type I product at Chanute and a Type III product at Dugway and Fort Polk. Sample 2 and Sample 3 were Type I and Type II products, respectively, at each of the three exposure locations. When the study began, most manufacturers specified an unreinforced membrane (either ASTM Type I or Type II) for ballasted systems. As shown in Table 1, the three ballasted membrane systems at Chanute Air Force Base were either Type I or Type II membrane materials. Field experience with PVC roofing has shown that some unreinforced PVC membranes (ASTM Type I) have undergone splitting, cracking and shattering in service, particularly those that are ballasted.⁹ As a consequence, ballasted PVC systems are seldom specified today. As will be discussed later in this report, the ballasted systems at Chanute (Site 1) experienced shattering and splitting problems.

ASTM D 4434 also contained a requirement that the minimum thickness of a PVC roofing sheet be 1.15 mm (0.045 in.). Note in Table 1 that all samples in the study were in conformance with this requirement.

Test program

The USACERL test program was designed to determine changes in mechanical and physical characteristics of the various PVC membranes at the three exposure locations. An initial set of tests was performed on each of the different materials cut from the membranes after installation to establish material characteristics of the new (unaged) membranes. For Sites 1 and 2, initial sampling was performed upon completion of the roofs. For Site 3, initial sampling occurred 3 months after the membranes were installed. Subsequently, samples were taken from each material at each site on a periodic basis, the target schedule being every six months for the first two years and annually thereafter. Five membrane sections, each measuring

Sample No. ^a	Test Site No.	Deck	Insulation	Vapor Retarder	Membrane Securement	Membrane ASTM Type ^b	Seam Weld	Thick. mm (in)
1	Chanute 1	Concrete	Polysocyanurate	2-ply organic	Ballasted	I	Heat	1.2 (0.046)
2	Chanute 1	Concrete	Polyisocyanurate Slip sheet/kraft	2-ply organic	Ballasted	I	Heat	1.3 (0.050)
3	Chanute 1	Concrete	Polyisocyanurate Perlite board	2-ply organic	Ballasted	II	Heat	1.2 (0.049)
1	Dugway 2	Concrete	Polyisocyanurate	none	Mech. attach (disks)	III	Heat	1.2 (0.047)
2	Dugway 2	Concrete	Polyisocyanurate Slip sheet/kraft	none	Mech. attach (battens)	I	Heat	1.2 (0.047)
3	Dugway 2	Concrete	Polyisocyanurate	none	Adhered	II	Heat	1.2 (0.047)
1	Fort Polk 3	Wood Plank	Polystyrene Slip sheet/fbgls	none	Mech. attach (disks)	III	Solvent	1.2 (0.047)
2	Fort Polk 3	Wood Plank	Polystyrene Slip sheet/kraft	none	Mech. attach (battens)	I	Solvent	1.4 (0.055)
3	Fort Polk 3	Wood Plank	Polystyrene Fiberboard	none	Adhered	II	Heat	1.2 (0.048)

^a For a given sample no. all materials were produced by the same manufacturer.

^b See the following paragraph for a description of the ASTM Categorization of membrane types.

Table 1. Summary of the PVC roof constructions.

PROPERTY MEASURED	ASTM METHOD [8]	ASTM VOLUME ^a
Plasticizer Content	ASTM D 3421	discontinued
Plasticizer Loss	ASTM D 1203	08.01
Tensile Strength	ASTM D 882	08.01
Elongation	ASTM D 882	08.01
Tear Strength	ASTM D 1004	08.01
Ply Adhesion	ASTM D 413	09.01
Abrasion Loss	ASTM D 3389	09.02
Thickness	ASTM D 1593 or ASTM D 751	08.01 09.02
Specific Gravity (Relative Density)	ASTM D 792, Procedure A-1	08.01
Water Vapor Transmission	ASTM E 96	04.06
Water Absorption	ASTM D 570	08.01
Dimensional Stability	ASTM D 1204	08.01
Seam Strength (Shear)	ASTM D 882	08.01
Seam Strength (Peel)	ASTM D 1876	15.06

^aIndicates the volume of the ASTM Book of Standards in which the test method is located.

Table 2. Properties measured and ASTM test methods used.

0.093 sq m (1 sq. ft.), were removed from each roof section: four from near each of the corners and one from the center. Final sampling was performed at 116, 95 and 113 months, respectively, for Sites 1, 2, and 3. These times were approximately 9%, 8 and 9% years, respectively.

Table 2 lists the properties measured and the ASTM test method designation. Note that the tensile, elongation and tear resistance tests were conducted only on the unreinforced membrane Types I and II. This was consistent with the test requirements of the later published ASTM D 4434. The ply adhesion test was only performed on the Type III unreinforced membrane (Sample 1 at Sites 2 and 3) as a measure of the adhesion of the PVC resin to the reinforcement.

The testing design was to conduct five measurements (one for each of the five membrane sections) of each property per material per exposure location per point in time. This was generally followed. But, for some properties of the initial (i.e., unaged) samples, more than five measurements were made. In contrast, in the case of abrasion loss, specific gravity, water absorption and water vapor transmission, only one initial measurement was performed. And, as will be evident from the plots to follow, some properties were not measured for every section removed from the roofs.

VISUAL INSPECTIONS

In general, each test roof was inspected by USACERL research personnel annually. The observations recorded over the first 6 to 7 years of the study indicated that the PVC roof membranes were performing satisfactorily. No observations caused concern about the watertightness of the roof or other aspects of membrane performance. The minor problems noted during these early inspections were generally associated with items such as details around flashings and penetrations, drains, gutters and debris.

As an example of a nonmembrane related problem, the roof areas near the north and south edges of the Chanute site, where Samples 1 and 2 were installed, were more steeply sloped (about 15 percent) than the main portion of the roof. The ballast material in those areas constantly slides from membrane and roof, stretching the membrane and damaging the edge detail and gutter. Alteration of the edge detail stopped the ballast from sliding into the gutter, but did not prevent stretching of the membrane (Figure 1). Although not membrane related, as noted below, this problem apparently contributed to membrane damage at a later date.

During the 5-year inspection of the roofing at Chanute, the membranes showed evidence of shrinkage as they were seen to have tightened in place. The shrinkage was not extensive enough to raise concerns about membrane performance. However, in December, 1989 during record cold temperatures, after about seven years of exposure, Sample 1 at Chanute catastrophically shattered across the entire unreinforced membrane (Figure 2). The membrane was replaced. The shattering was typical of that experienced by other PVC roof membranes during the late 1980s.⁹ All such failures have reportedly occurred with unreinforced membranes, many of which were ballasted. The failures have been attributed to stress build up in the membranes due to shrinkage resulting



Figure 1. Stretching of the membrane that occurred with Samples 1 and 2.

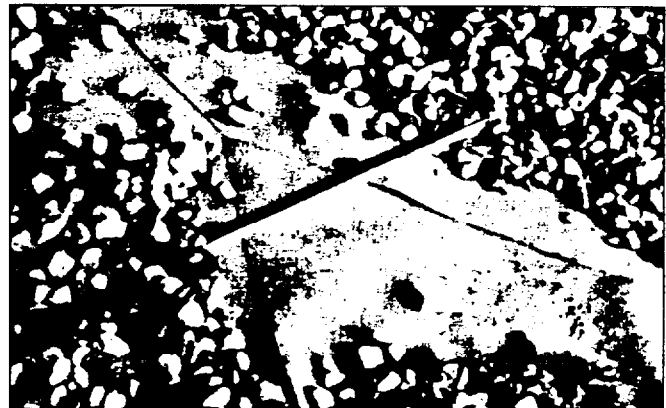


Figure 2. Shattering of the membrane of sample at Chanute.

from plasticizer loss. Unreinforced membranes would be more likely to have catastrophic failures because reinforcement might be expected to arrest splits or cracks. The increased risk of failure with ballasted systems has been discussed by Pastuska,¹⁰ who concluded that a mixture of water, mud, microorganisms and oxygen on the ballasted membrane surface tends to increase plasticizer loss.

For 10 years, the inspections at Chanute indicated satisfactory performance of membrane Samples 2 and 3. In the spring of 1994 (after about 11 years of service), both samples experienced problems. In the case of Sample 2, the membrane shattered in the area along the south edge of the building where it had been stretched by the sliding ballast (Figure 3). Although the area of shattering was limited, the entire membrane was replaced because of the risk that the unshattered section of the membrane might also fail catastrophically. In the case of Sample 3, two splits occurred in the field of the membrane. The splits were repaired as the majority of the membrane was considered still functional.

Performance of all PVC membranes at Dugway (Site 2) was satisfactory through 1989 (about eight years of service). However, shortly thereafter, non-roofing-related work on the roof resulted in punctures and cuts of the membranes to the extent that repair was not considered practical. Consequently, the Dugway membranes were replaced.

The three membranes at Fort Polk (Site 3) generally have performed satisfactorily for more than 10 years. However, the roof has not been leak free. Some mechanical fasteners used for securing the roofing backed out from the deck and punctured the membranes. Fastener backout without membrane puncture was observed about three years into the study, but it was late into the study when the puncturing occurred. No judgment was made as to whether the puncturing should be assigned to poor fastener performance or poor membrane performance. The punctures were repaired, and the roof was still functional at the conclusion of the study.

ANALYSIS OF TEST DATA

Treatment and presentation of data

The data are presented graphically (Figures 4 through 12) and, for each property, one plot gives the measured value ver-

sus time for a given membrane sample (Samples 1, 2 and 3) and installation site (Sites 1, 2 and 3). Thus, in general, nine plots are given for each property (three samples times three sites) in each figure. By examining a set of plots across a row, any differences between the samples at a fixed site are observed. Likewise, by considering a set of plots down a column, the effect of site on a fixed sample is seen. All individual data points are plotted, but the plots do not distinguish overstrikes.

The analysis of the data was conducted using a linear model:

$$\text{response} = A_0 + A_1 t$$

where t = time in months
 A_0 = a constant (the intercept)
 A_1 = a constant (the slope)

This model was selected after reviewing the plots of measured property value versus time, which in general did not support the selection of a more complex model.

Each plot contains the best-fit straight line for a set of data for each sample at each site. In slightly over half the analyses, the slope was statistically different from zero (i.e., the magnitude of the slope was at least three times greater than its standard deviation). In some cases where the slope was not statistically different from zero, the data exhibited no appreciable time dependence. In others, the apparent change in property over time was overshadowed by the large uncertainty in the estimated slope due to a large scatter in the data.

To aid interpretation of the results, tables for each property (except for plasticizer content) were prepared to summarize:

- The initially measured average property value (M_i).
- The estimate of the intercept (A_0) at initial time.
- The slope of the line (A_1).
 Note: In the tables, the units for A_1 are [(the units for A_0) x months⁻¹].
- Whenever the slope was statistically different from zero, the magnitude of the estimated value was at least three times its standard deviation; in these cases, the column contains a yes.
- An estimate of the percent change in the property over 100 months calculated using the model for each data set. The indicated uncertainty in the estimated percent change represents one standard deviation.

The estimated percent change in a property was taken as an indicator of how much that property changed during the study. A nominal study period of 100 months was used in the estimate because it was within the range of time over which the sampling at the three sites was performed. The estimate of percent change in property value provides a uniform means of comparing the properties as a function of sample and site and determining those that underwent the greatest change over time. A summary of the variability in the descriptors M_i , A_0 and A_1 is given in the appendix of reference USACERL Technical Report 96/23.⁶

The following sections contain the tables and plots of the data analyses for selected properties. Comments on key observations accompany each set of plots and table. Many of these comments focus on the change in properties of the bal-



Figure 3. Sample 2 at Chanute shows the shattered membrane where it was stretched by the sliding ballast.

lasted roofs at Chanute (Site 1) because of the less-than-satisfactory performance at this site. The intent was to determine whether changes in any of the measured properties were consistently different for samples from Chanute than for samples from Dugway and Fort Polk. Additionally, in reviewing the results of the seam strength tests, a point of evaluation was whether solvent-welded seams performed differently than heat-welded seams. As a note regarding all properties, it was observed that the measured average property value (M_t) and the estimate of the true value at initial time (A_0) generally were in agreement.

This summary paper does not show the data for abrasion, water absorption and dimensional stability because no important differences between the Site 1 sample and Sites 2 and 3 samples were observed. Although no such differences were found for the elongation data, they are presented to illustrate this fact.

Plasticizer content and plasticizer loss

The first properties presented are those related to plasticizer loss. However, the measurement of plasticizer content was not included in the study until 1989, when it was conducted only on retained initial samples from Chanute and Fort Polk, and those cut from all roofs after about five years of exposure. Initial samples from Dugway had not been retained. The membrane materials specified at Dugway and Fort Polk were the same but probably from different lots. Thus, the initial plasticizer contents of the Dugway materials might be expected to be comparable to those at Fort Polk.

The following comments may be made about the plasticizer content results given in Table 3:

- The data set is limited in that measurements were made only for the original membrane material and after the roofs had been in service for about five to six years. Thus, only trends can be noted.
- For each of the three samples, the measured initial plasticizer contents were essentially the same at Chanute and Fort Polk.
- Assuming that, for each of the three samples, the initial Dugway materials were comparable to those at Chanute and Fort Polk, all PVCs lost plasticizer over the five to six years of exposure. The range was from about 15 to 30 percent.
- In most cases, little difference was seen between many of

the plasticizer content values after five to six years of exposure. For six of the nine measurements, the average plasticizer contents of the aged samples ranged from 23 to 26 percent. The others were higher.

- The ballasted aged Sample 1 at Chanute showed the lowest average plasticizer content; this was the membrane that experienced catastrophic shatter. The exposed aged Sample 1 at Fort Polk had the second lowest average value; this membrane has performed satisfactorily. Considering the variation in the data, these two aged samples had essentially the same plasticizer content after about five to six years of service. Chanute is located in the North; whereas Fort Polk is in the South.
- Similarly, the average plasticizer content for aged Sample 2 at Chanute was the same as that of aged Sample 2 at Fort Polk. Chanute experienced problems; whereas Fort Polk has performed satisfactorily.
- In the case of Sample 3, the ballasted membrane at Chanute lost more plasticizer than the exposed membranes at Dugway and Fort Polk.

The plasticizer loss test "drives" plasticizer from the sheet material. The loss value is determined by heating the specimen removed from the roof and measuring the mass lost during heating. If the amount lost during the test decreases with time of field exposure, it may be that the plasticizer was lost during field exposure.

The following comments may be made about the plasticizer loss results given in Table 4 and Figure 4:

- For Site 2, no initial data were available to include in the analysis. The first measurements were made when the Site

SITE Membrane Age	PLASTICIZER CONTENT, % by mass		
	Sample 1	Sample 2	Sample 3
Site 1 (Chanute) original	31 ± 3	32 ± 2	35 ± 1
68 months	23 ± 2	26 ± 1	25 ± 1
Site 2 (Dugway) original	—	—	—
62 months	26 ± 1	28 ± 2	31 ± 1
Site 3 (Fort Polk) original	30 ± 1	31 ± 1	34 ± 1
60 months	25 ± 1	26 ± 2	29 ± 1

Note: This property was not measured for unaged samples from Site 2.

Table 3. Plasticizer content measurements (ASTM D 3421).

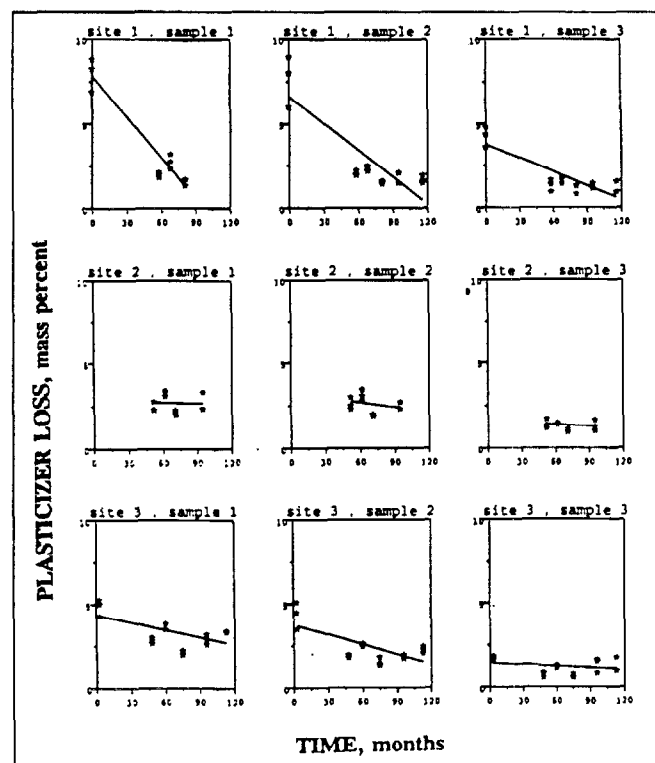


Figure 4. Results of the plasticizer loss tests.

Sample No.	Site No.	M, % mass	A, % mass	A _i	Stat. Sign.	Est. Change in 100 Months %
1	1	8.1	7.8	-0.0810	yes	-103 ± 16
1	2	2.5	2.8	-0.0019	no	-7 ± 39
1	3	4.9	4.4	-0.0145	no	-33 ± 14
2	1	7.7	6.6	-0.0053	yes	-80 ± 19
2	2	2.7	3.2	-0.0087	no	-27 ± 32
2	3	4.4	3.7	-0.0192	yes	-51 ± 18
3	1	4.3	3.8	-0.0273	yes	-72 ± 17
3	2	1.5	1.6	-0.0032	no	-2 ± 4
3	3	1.8	1.5	-0.0031	no	-21 ± 22

Note: This table reflects the change in the percent of plasticizer lost by test method ASTM D1203 and not the absolute amount of plasticizer lost.

Table 4. Summary of plasticizer loss results (ASTM D 1203).

2 samples were 52 months old. For the available data at Site 2, none of the slopes of the regression lines were statistically different from zero. This may be an indication that the plasticizer available for loss during the test may have reached a constant value when the series of tests of Site 2 samples began. Note, in a similar observation, that the samples at Sites 1 and 3 showed little variation in the plasticizer loss values measured after 48 months.

- For each sample, the values of plasticizer loss were greater (by a factor of about 2) at Site 1 than at Site 3. Reasons for this observation (e.g., material variability, test method variability, or unknown factors related to shipping, installation or initial outdoor exposure) are not known.
- For Samples 1 and 2, the final values of plasticizer loss were lower at Site 1 (ballasted membranes) than at Site 3 (exposed membranes). For Sample 3, the final values were about the same at Site 1 and at Site 3.
- A comparison of the estimated percent change over 100 months for the samples at Sites 1 and 3 has little meaning considering the greater initial values at Site 1 versus Site 3. It is noted that, for the samples, four of the six regression lines had slopes statistically different from zero.

Tensile strength

The following comments may be made about the tensile strength results given in Table 5 and Figure 5:

- Initial tensile strength for Sample 1 was stronger than Sample 2, which was stronger than Sample 3.
- With the exception of Sample 2 at Site 2, the slopes of the regression lines were positive, indicating an increase of strength with time. With the exception of Sample 2 at Site 3 and Sample 3 at Site 2, the slopes were statistically different from zero.
- Sample 3 at Site 1 showed the largest estimated percent increase over time (68 percent). The data for this sample had considerable scatter at the longer exposure times, which may have contributed to the estimated increase.

Sample No.	Site No.	M, MPa (psi)	A, MPa (psi)	A _i , S.I. (cust.)	Stat. Sign.	Est. Change in 100 Months %
1	1	16.6 (2412)	16.7 (2429)	0.066 (9.6)	yes	40 ± 10
2	1	15.8 (2286)	15.3 (2226)	0.028 (4.05)	yes	18 ± 3
2	2	14.5 (2104)	15.0 (2169)	-0.010 (-1.52)	yes	-7 ± 2
2	3	15.3 (2112)	14.6 (2112)	0.0020 (0.29)	no	1 ± 2
3	1	12.2 (1776)	11.6 (1686)	0.079 (11.42)	yes	68 ± 11
3	2	10.3 (1493)	10.2 (1485)	0.0097 (1.41)	no	9 ± 3
3	3	11.6 (1677)	11.4 (1647)	0.018 (2.66)	yes	16 ± 3

Note: This property was not measured for Sample 1 at Sites 2 and 3.

Table 5. Summary of tensile strength results (ASTM D 882).

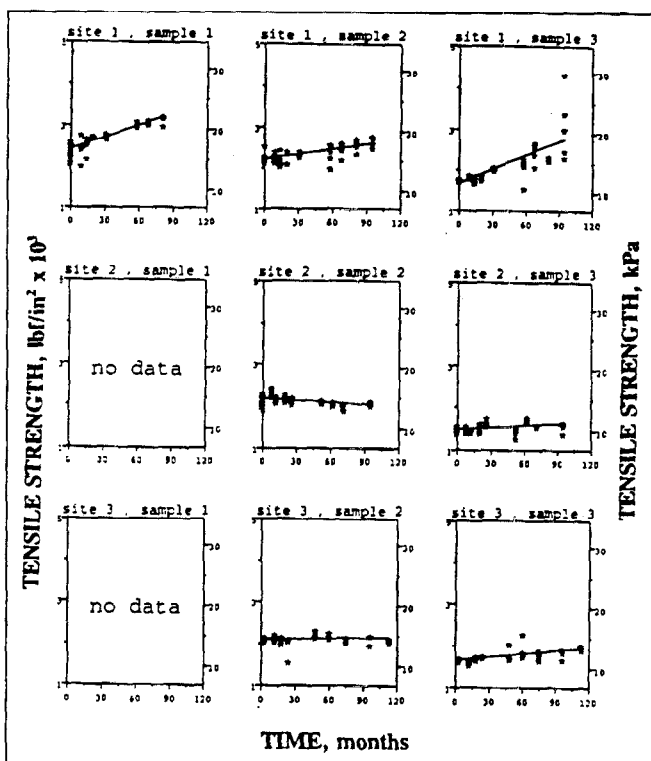


Figure 5. Results of the tensile strength tests.

- For the data set, the three samples at Site 1 showed the largest estimated percent increase. Site 1 membranes were ballasted and experienced problems in service.
- The largest estimated percent change for a nonballasted system was found for Sample 3 at Site 3. This value (16 percent) was comparable to that (18 percent) found for the ballasted Sample 2 at Site 1.

Sample No.	Site No.	M, % mass	A, % mass	A, % mass	Stat. Sign.	Est. Change in 100 Months %
1	1	269	264	-0.50	yes	-19 ± 6
2	1	290	285	-0.42	yes	-15 ± 4
2	2	259	265	-0.55	yes	-21 ± 3
2	3	256	254	-0.62	yes	-24 ± 4
3	1	254	256	-0.99	yes	-39 ± 11
3	2	253	245	-0.41	no	-17 ± 7
3	3	232	235	-0.26	yes	-11 ± 4

Note: This property was not measured for Sample 1 at Sites 2 and 3.

Table 6. Summary of elongation results (ASTM D 882).

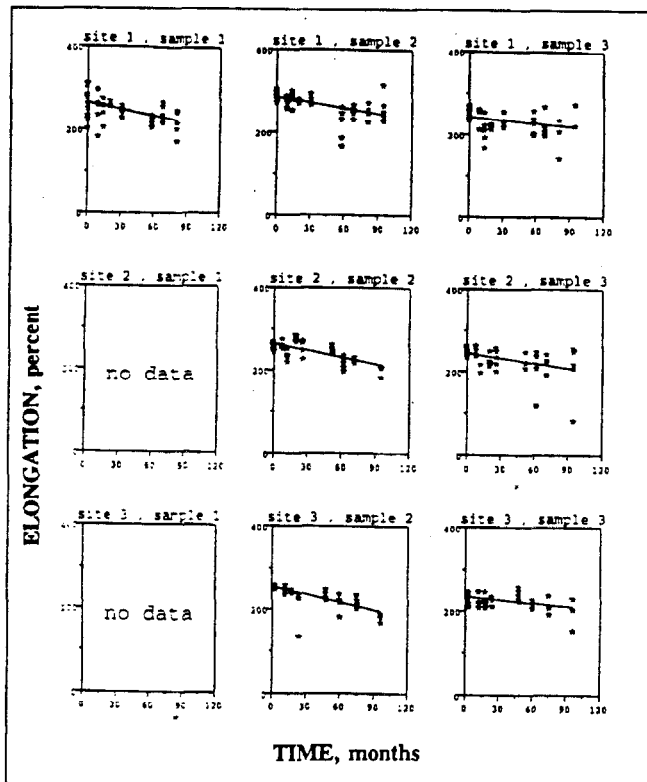


Figure 6. Results of the elongation tests.

Elongation

The following comments may be made about the elongation results given in Table 6 and Figure 6:

- For all samples, the initial elongations were comparable, ranging from about 230 to 290 percent.
- All samples showed a decrease in elongation over time. The slopes of the regression lines were statistically different from zero in six of the seven cases. The exception was Sample 3 at Site 2, which was nearly significant. (The estimated value of the slope was 2.6 times its standard deviation.)

- The ballasted Sample 3 at Site 1 had an estimated decrease that was greater than those of the exposed Sample 3 at Sites 2 and 3.
- The ballasted Sample 2 at Site 1 had an estimated decrease that was less than those found for the nonballasted Sample 2 at Sites 2 and 3.

Sample No.	Site No.	M, N (lbf)	A, N (lbf)	A, S.I. (cust.)	Stat. Sign.	Est. Change in 100 Months %
1	1	62.7 (14.1)	59.6 (13.4)	0.445 (0.100)	yes	75 ± 8
2	1	56.9 (12.8)	56.0 (12.6)	0.254 (0.057)	yes	45 ± 5
2	2	56.9 (12.8)	57.8 (13.0)	0.022 (0.005)	no	4 ± 3
2	3	49.4 (11.1)	52.0 (11.7)	0.111 (0.025)	yes	21 ± 5
3	1	70.3 (15.8)	66.7 (15.0)	0.325 (0.073)	yes	49 ± 6
3	2	70.3 (15.8)	68.9 (15.5)	0.066 (0.015)	no	10 ± 6
3	3	71.6 (16.1)	69.8 (15.7)	0.129 (0.029)	yes	18 ± 4

Note: This property was not measured for Sample 1 at Sites 2 and 3.

Table 7. Summary of tear strength results (ASTM D 1004).

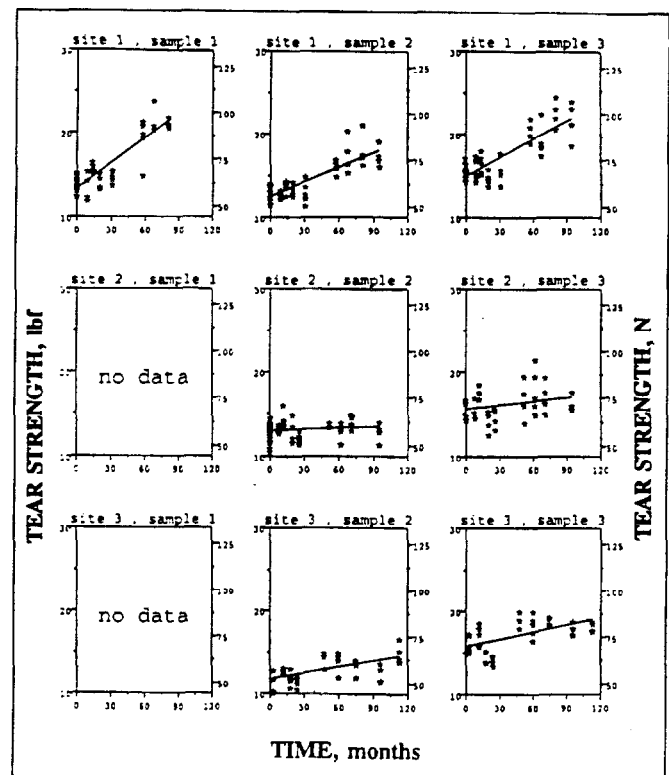


Figure 7. Results of the tear strength tests.

Tear strength

The following comments may be made about the tear strength results given in Table 7 and Figure 7:

- Sample 3 had the greatest initial tear strength; Sample 2 had the lowest value.
- All samples showed an increase in tear strength over time. With the exceptions of Samples 2 and 3 at Site 2, the slopes of the regression lines were statistically different from zero:
- The ballasted roofs at Site 1 showed the greatest estimated increase; the values were more than twice the estimated change for any of the nonballasted roofs at Sites 2 and 3.

Thickness

The following comments may be made about the thickness results given in Table 8 and Figure 8:

- With the exception of Sample 1 at Site 3, the thickness of the samples at all sites decreased over time, ranging from 5 to 18 percent. In these cases, the negative slope of the regression line was statistically different from zero. It is not known whether the reduction in thickness was associated with factors such as relaxation shrinkage, loss of plasticizer, erosion of the surface, or, in the case of ballasted membranes, creep associated with the load of the ballast.
- The ballasted samples at Site 1 experienced the greatest estimated decrease in thickness.

These thickness results can be compared with limited data recently reported¹¹ by the joint CIB/RILEM Committee on Membrane Roofing Systems. This Committee was investigating the use of thermoanalytical techniques for evaluating the stability of membrane materials, including PVC, to outdoor

Sample No.	Site No.	M, mm (in)	A, mm (in)	A.x10 ⁴ S.I. (cust.)	Stat. Sign.	Est. Change in 100 Months %
1	1	1.2 (0.046)	1.2 (0.046)	-1803 (-71)	yes	-15 ± 1
1	2	1.3 (0.050)	1.3 (0.050)	-635 (-25)	yes	-5 ± 1
1	3	1.2 (0.049)	1.2 (0.049)	-76 (-3)	no	<-1 ± 3
2	1	1.2 (0.047)	1.2 (0.047)	-1524 (-60)	yes	-13 ± 1
2	2	1.2 (0.047)	1.2 (0.048)	-1321 (-52)	yes	-11 ± 1
2	3	1.2 (0.047)	1.2 (0.047)	-1143 (-48)	yes	-10 ± 1
3	1	1.2 (0.047)	1.2 (0.047)	-2134 (-84)	yes	-18 ± 1
3	2	1.4 (0.055)	1.4 (0.054)	-1524 (-60)	yes	-11 ± 3
3	3	1.2 (0.048)	1.3 (0.050)	-838 (-33)	yes	-7 ± 2

Table 8. Summary of thickness results (ASTM D 1593 or D 751).

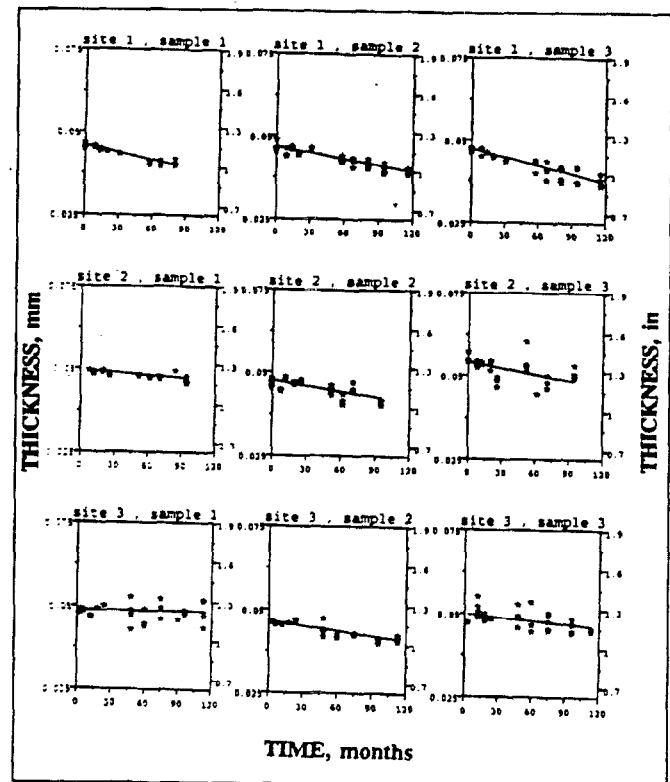


Figure 8. Results of the thickness tests.

and laboratory exposures. One criterion for stability was that the change in glass transition temperature (T_g) upon exposure not exceed 8°C (46°F). For one outdoor exposure,¹¹ the T_g determined by torsional pendulum analysis (TPA) was found to have increased by 15°C (59°F). The committee also found that the Haifa-exposed specimen displayed a decrease in thickness of about 4 percent during the exposure period, which was considered to be relatively high. The PVC specimens subjected to other exposures under which they were considered to be stable showed little decrease in thickness. Decrease in thickness may be associated with loss of plasticizer and shrinkage. The CIB/RILEM Committee questioned whether measurements of membrane material thickness over time would provide a relatively easy characterization technique for following the potential deterioration of PVC products.

The finding in the present study that PVC thickness measurements discriminated between acceptably and unacceptably performing samples is similar to the CIB/RILEM observation¹¹ that a specimen, relatively unstable to its exposure environment, lost more thickness than relatively stable specimens. Studies to investigate the validity of an hypothesis that thickness measurements might be used as an indicator of PVC stability to its environment are needed.

Specific gravity

The following comments may be made about the specific gravity results given in Table 9 and Figure 9:

- The initial specific gravities of all samples were comparable, ranging from 1.25 to 1.33.

Sample No.	Site No.	M, sp gr	A, sp gr	A, S.I.	Stat. Sign.	Est. Change in 100 Months %
1	1	1.27	1.26	0.0009	yes	7 ± 0.8
1	2	1.28	1.27	0.0004	yes	3 ± 0.5
1	3	1.27	1.26	0.0004	yes	3 ± 0.6
2	1	1.27	1.26	0.0007	yes	6 ± 0.4
2	2	1.33	1.32	0.0007	yes	6 ± 0.6
2	3	1.32	1.31	0.0007	yes	5 ± 0.5
3	1	1.25	1.24	0.0008	yes	6 ± 1
3	2	1.26	1.26	0.0003	no	3 ± 1
3	3	1.28	1.26	0.0004	yes	3 ± 0.5

Table 9. Summary of specific gravity results (ASTM D 792).

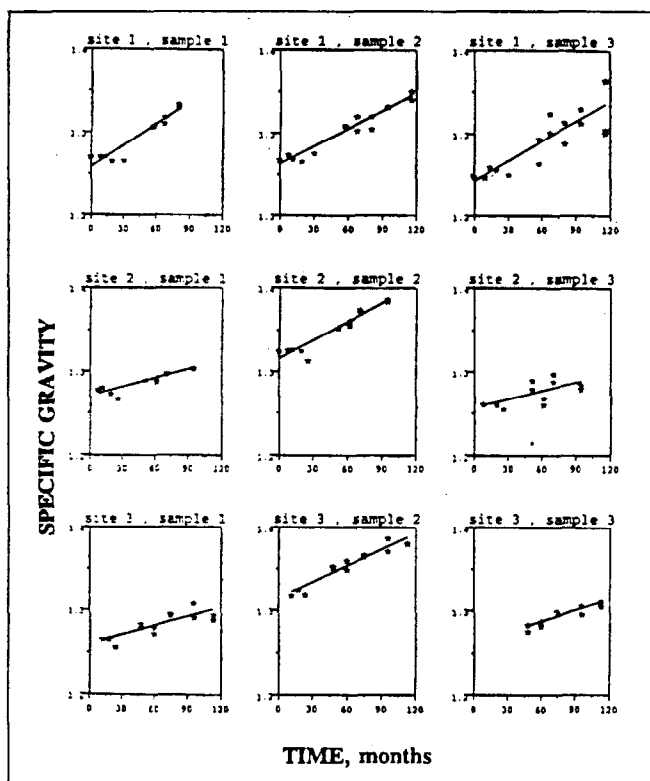


Figure 9. Results of the specific gravity tests.

- All samples at all sites exhibited an increase in specific gravity over time. With the exception of Sample 3 at Site 2, the slopes of the regression lines were statistically different from zero.
- The estimated percent changes for the ballasted Samples 1 and 3 at Site 1 were about twice that for these two unballasted samples at Sites 2 and 3.
- In the case of Sample 2, the estimated percent change for the ballasted material at Site 1 was essentially the same as that for the unballasted materials at Sites 2 and 3.

Sample No.	Site No.	M, g/Pa·s·m (perm)	A, g/Pa·s·m (perm)	A, S.I. (cust.)	Stat. Sign.	Est. Change in 100 Months %
1	1	1.3 (0.23)	1.4 (0.24)	-0.010 (-0.0018)	yes	-74 ± 12
1	2	1.3 (0.23)	1.2 (0.21)	-0.0029 (-0.0005)	no	-22 ± 11
1	3	1.5 (0.27)	1.4 (0.25)	-0.0034 (-0.0006)	yes	-25 ± 10
2	1	1.4 (0.24)	1.4 (0.24)	-0.0051 (-0.0009)	yes	-39 ± 10
2	2	1.5 (0.26)	1.4 (0.25)	-0.00023 (-0.00004)	no	-2 ± 12
2	3	1.5 (0.27)	1.3 (0.22)	0.0011 (0.0002)	no	8 ± 16
3	1	1.4 (0.24)	1.3 (0.23)	-0.0017 (-0.0003)	no	-15 ± 20
3	2	1.3 (0.23)	1.4 (0.24)	-0.00017 (-0.00003)	no	1 ± 7
3	3	1.4 (0.25)	1.4 (0.25)	-0.0034 (-0.0006)	no	-25 ± 11

 Note: WVT values given in metric units are times 10⁻⁸.

Table 10. Summary of WVT results (ASTM E 96).

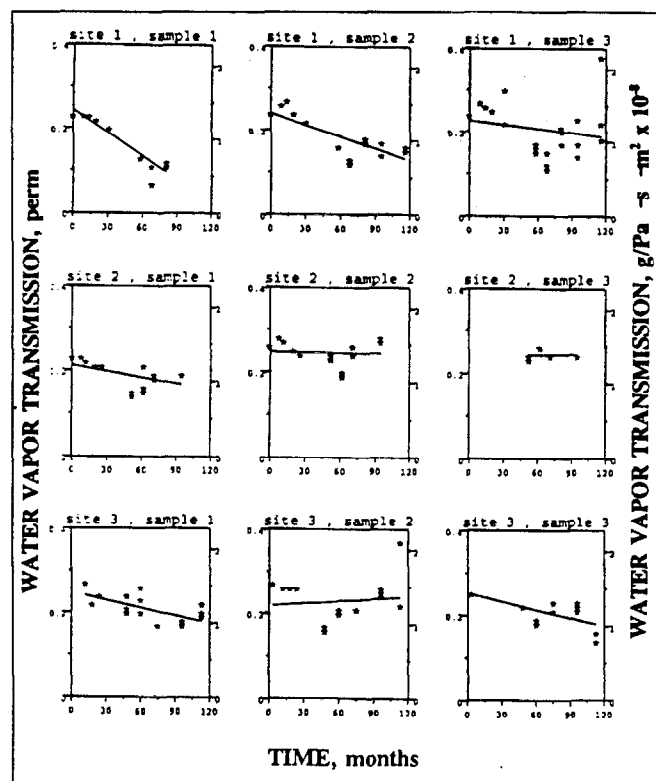


Figure 10. Results of the water vapor transmission tests.

Water vapor transmission

The following comments may be made about the water vapor transmission (WVT) results given in Table 10 and Figure 10:

- Most samples displayed decreases in WVT over time. However, only three (Sample 1 at Sites 1 and 3 and Sample 2 at Site 1) had regression lines with slopes statistically different from zero.
- In most cases where the slope was not statistically different from zero, considerable scatter in the data occurred.
- For Samples 1 and 2, the rate of decrease in WVT was considerably greater at Site 1 (ballasted installation) than at the other two sites.
- For Sample 3, the ordering is unclear due to the large uncertainties in the estimated changes at Sites 1 and 3.

Seam shear strength

The following comments may be made about the seam shear strength results given in Table 11 and Figure 11:

- The initial shear strengths of the Type III reinforced membranes (Sample 1 at Sites 2 and 3 [see Table 1]) were greater than those of the Type I (Sample 1 at Site 1 and Sample 2 at all sites) and Type II (Sample 3 at all sites) membranes.
- The initial shear strengths of the solvent-welded seams, Samples 1 and 2 at Site 3 (Table 1), were comparable to those of the heat-welded seams (i.e., all other samples).
- The majority of the seam shear strengths increased over time. For these materials, the positive slopes of the regression lines were statistically different from zero. The range of estimated percent change was 7 to 35 percent.
- The solvent-welded seams, Samples 1 and 2 at Site 3, showed increases in strength of 30 and 7 percent, respectively. These values essentially bracketed those of the heat-welded seam samples (i.e., all other samples).

Sample No.	Site No.	M _i kN/m (lbf/in)	A _i kN/m (lbf/in)	A _i S.I. (cust.)	Stat. Sign.	Est. Change in 100 Months %
1	1	13.9 (79.3)	14.4 (82.1)	0.051 (0.29)	yes	35 ± 4
1	2	26.1 (149.2)	27.3 (156.0)	0.054 (0.31)	yes	20 ± 3
1	3	20.4 (116.3)	22.8 (130.2)	0.068 (0.39)	yes	30 ± 8
2	1	13.3 (76.2)	13.2 (75.4)	0.035 (0.20)	yes	26 ± 4
2	2	14.4 (82.3)	14.2 (81.1)	0.001 (0.004)	no	0.5 ± 3
2	3	14.0 (79.8)	14.1 (80.4)	0.011 (0.06)	yes	7 ± 2
3	1	13.3 (76.1)	13.0 (74.5)	0.039 (0.22)	yes	30 ± 3
3	2	13.0 (74.0)	11.7 (66.8)	0.005 (0.03)	no	5 ± 6
3	3	13.5 (77.0)	13.2 (75.6)	0.014 (0.08)	yes	11 ± 2

Table 11. Summary of seam shear strength results (ASTM D 882).

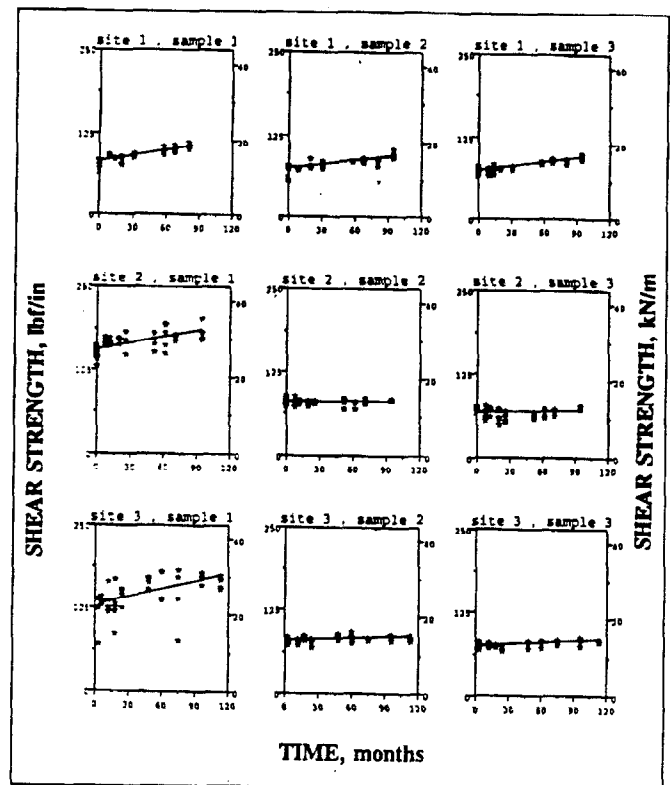


Figure 11. Results of the seam shear strength tests.

- The estimated percent increases in seam shear strength for the ballasted membranes at Site 1 were found at the high end of the range, with values from 26 to 35 percent.
- Samples 2 and 3 at Site 2 experienced no statistically significant change in seam shear strength with time.

Seam peel strength

During testing of the membrane specimens, the peel test was found to be difficult to conduct on the specimens taken from roofs. The difficulty involved creating "flaps" on the test specimens, either by partial delamination of the seam or addition of a PVC strip on the seam to hold the specimens in the grips of the testing machine.

The following comments may be made about the seam peel strength results given in Table 12 and Figure 12:

- None of the changes in seam peel strength had regression lines with slopes statistically different from zero. Considerable scatter was evident in the data in all cases. The scatter may be associated with the difficulties encountered in performing the peel tests.
- Important differences between the peel strengths of seams of the various samples may have been expected only if the bonding processes during membrane installation had been inadequate. This was unlikely in this study as all seams performed satisfactorily over the service lives of the membrane samples.

CONCLUSIONS AND COMMENTARY

The intent of the 10-year field exposure study of the performance of PVC roofing membrane materials installed at Chanute Air Force Base, Illinois, Dugway Proving Ground.

Sample No.	Site No.	M, kN/m (lbf/in)	A, kN/m (lbf/in)	A, S.I. (cust.)	Stat. Sign.	Est. Change in 100 Months %
1	1	7.8 (44.4)	6.1 (35.0)	0.023 (0.134)	no	38 ± 21
1	2	7.1 (40.6)	6.0 (34.2)	-0.011 (-0.061)	no	-18 ± 13
1	3	3.5 (19.8)	3.9 (22.3)	0.007 (0.039)	no	17 ± 3
2	1	4.5 (25.6)	5.0 (28.4)	0.009 (0.054)	no	19 ± 14
2	2	2.4 (13.7)	2.4 (13.9)	-0.001 (-0.005)	no	-4 ± 16
2	3	2.4 (13.5)	2.2 (12.3)	0.007 (0.042)	no	34 ± 14
3	1	6.2 (35.5)	6.5 (37.2)	0.008 (0.046)	no	12 ± 10
3	2	4.4 (25.2)	3.2 (18.3)	0.012 (0.068)	no	37 ± 41
3	3	8.9 (50.8)	7.7 (44.2)	-0.009 (-0.050)	no	-11 ± 14

Table 12. Summary of seam peel strength results (ASTM D 1876).

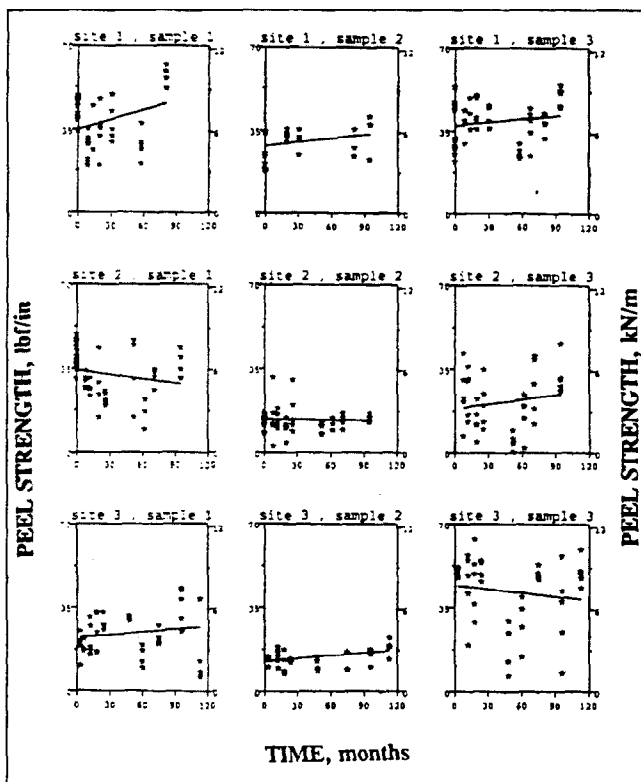


Figure 12. Results of the seam peel strength tests.

Utah, and Fort Polk, Louisiana, was to compare the results of laboratory tests of membrane properties with the observations noted on field performance. Periodically over the 10 years, USACERL obtained samples from the roofs for laboratory characterization of selected mechanical and physical

properties. Additionally, the roofs were visually inspected to evaluate their performance. The performance was generally satisfactory at Dugway and Fort Polk but problems relating to membrane shattering and splitting occurred at Chanute. A major difference in the roof construction at Chanute was that the membranes were ballasted; at Dugway and Fort Polk, they were mechanically attached or fully adhered. Experience with the performance of PVC roofing has shown that ballasted systems may have an elevated risk of poor performance.

Note that the data, analyses and other information in this report are for PVC membrane materials manufactured over a decade ago. Changes in PVC roofing membrane technology have occurred since that time, as evidenced by the revisions to ASTM Standard Specification D 4434 (1996). Because of changing technology, readers are cautioned against broadening the interpretation of the results of this study to current PVC membrane materials without supporting data to do so.

Because of the less-than-satisfactory performance at Chanute, statistical analysis of the 10-year PVC data set focused on whether changes in any of the measured properties were consistently different for samples from Chanute than for samples from Dugway and Fort Polk. The properties measured during the study were: plasticizer content, plasticizer loss, tensile strength, elongation, tear strength, ply adhesion, abrasion loss, thickness, specific gravity, water vapor transmission, water absorption, dimensional stability, seam shear strength and seam peel strength.

The results of the analyses indicated that most of the measurements did not discriminate between the performance of the PVC membranes at Chanute and those at Dugway and Fort Polk. This indiscriminate performance may be because a field experiment has hidden variables that are difficult to control and may have significant influence on the test results (i.e., the variability of membrane materials installed in large quantities at different locations and times).

As an illustration of the nondiscriminating nature of the results, it was observed that, as may have been expected, all samples at the three sites lost plasticizer during the exposure period. Two of the three samples from Chanute did not lose significantly more plasticizer than those from Dugway or Fort Polk. The limited data on plasticizer content showed that the aged membrane sample that eventually shattered at Chanute had the lowest average content. However, these data also indicated that, with the exception of the shattered membrane at Chanute, the aged Sample 1 that performed well at Fort Polk had, on the average, equal or less plasticizer than any of the other samples at the other sites. Also, the plasticizer loss test gave mixed results. While the tests implied that aged membrane Samples 1 and 2 had less plasticizer at Chanute than at Dugway and Fort Polk, tests of the aged membrane Sample 3 suggested that samples from the three sites had about the same amount.

Only in the case of tear strength and thickness were the changes larger for the ballasted membranes at Chanute than for the nonballasted membranes at Dugway and Fort Polk. In general, for all samples, tear strength increased with exposure time, whereas the thickness decreased with time. It is questioned whether loss of plasticizer would cause embrittlement of the PVC material which, in turn, would increase tear resistance. Similarly, plasticizer loss could shrink the membrane and be displayed as a loss in thickness. The limited

finding on thickness measurements possibly discriminating between acceptably and unacceptably performing PVC samples was similar to that from the CIB/RILEM Committee. It reported that a PVC specimen, relatively unstable to its exposure environment, lost more thickness than relatively stable specimens. The possibility that either thickness or tear strength measurements may provide an indicator of membrane stability to its environment need to be investigated in the laboratory to reach a definitive conclusion.

For a number of other tests, the results showed that changes in the measured property were greater for two, but not all three, of the ballasted membranes at Chanute than for the nonballasted membranes at Dugway and Fort Polk. Included here were tensile strength, specific gravity and water vapor transmission. Tests that showed no distinction between the ballasted Chanute membranes and the nonballasted membranes were elongation, abrasion loss, water absorption and dimensional stability.

Finally, the shear and peel tests on the seams did not detect differences between heat-welded and solvent-welded seams. This finding may have been expected, as both types of seams performed satisfactorily over the duration of the study. This would imply that, for the test roofs, the two seam fabrication techniques provided acceptable bonds. The initial shear strengths for both types of seams were comparable, and generally increased with exposure time. Seam peel strengths had considerable data scatter and differences were not statistically significant.

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